NASA TT F-9798

NASA TT F-9798

PLASMA ENGINES AND THEIR POTENTIALITIES

Yu.Berestov

Translation of "Plazmennyye dvigateli i ikh vozmozhnosti".
Aviatsiya i Kosmonavtika, Vol.48, No.8, pp.64-9, 1965.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON DECEMBER 1965

NASA TT F-9798

PLASMA ENGINES AND THEIR POTENTIALITIES **/64

Yu.Berestov*

13485

General aspects and future possibilities of the plasma engine are reviewed briefly, with description of its use in the navigation system of the Mars probe Zond-2. A suggested classification of plasma engines, according to working medium, type of magnetic field, and type of heating is given. Diagrammatic views of crossed-field plasma accelerators, with cryogenic superconducting materials for the electromagnet windings and making use of Lorentz forces for accelerating the plasma are included. Preference is given to plasma engines with acceleration in their own magnetic field, using coaxial electrodes and/or front discharge. A 50% increase in efficiency is expected from magnetoplasma engines using Hall currents.

Plasma engines were first successfully tested on board the Soviet space platform and probe Zond-2. At an enormous distance from the earth, these devices obeyed human commands and worked in the navigation system.

Plasma engines belong to a novel type of electric jet engines in which the thrust is created by using electric energy. A feature of plasma, an electrically neutral mixture of positively and negatively charged and neutral particles, is its electric conductivity. This property is utilized in plasma engines,

* Docent and Cand. in Tech. Sci.

** Numbers in the margin indicate pagination in the original foreign text.

either to heat matter to a high temperature or to accelerate the plasma by means of forces acting on a conductor in a magnetic field (Lorentz forces).

Another variant of the electrojet engine, the ion engine, in which charged particles are accelerated in a strong electrostatic field, will not be discussed in this article.

Why is electricity used? It is well known that the thrust of a rocket engine equals the discharge of the mass of the working fluid per second, multiplied by the exhaust velocity. However, the performance of a given engine is evaluated by the specific thrust (i.e., the thrust per kilogram of matter discharged per second), which is directly proportional to the exhaust velocity.

The exhaust velocity, in turn, depends on the absolute temperature of the working medium ahead of the jet nozzle, on the molecular weight of the working fluid, and on the pressure drop. In existing rocket engines, at maximum combustion temperature of the fuel components in a liquid-fuel rocket engine (LRE) and moderate molecular weight of the combustion products, a specific thrust of the order of 300 - 350 $\frac{kg \cdot sec}{kg}$ can be obtained.

In a nuclear rocket engine (NRE), if hydrogen (which is a working medium of minimum molecular weight) is used, specific thrusts up to 900 - 1200 $\frac{kg \cdot sec}{kg}$ are conceivable. In an NRE, the heating of the working fluid is limited only by the thermal resistance of the fuel elements of the reactor. A further increase in the specific thrust of a nuclear engine requires transition to a liquid or gaseous reactor core, which raises extremely complex engineering problems.

The use of electric energy makes it possible to overcome these obstacles to a further increase in the specific thrust of liquid and nuclear rocket engines. For instance, a temperature of 5000 - 15,000°K or even higher can be obtained only by electric heating in an arc discharge or in a high-frequency field.

If the combustion chamber or the nuclear reactor is replaced by an electric heater, a specific thrust ten times as great can be obtained. Engines based on this principle are known as electrothermal rocket engines (ETRE).

Not only the simple thermal acceleration of the working fluid but also other electrical systems permit a utilization of the capacity of such working fluids to conduct an electric current at high temperatures (in the plasma state), and allow the use of a magnetic field to increase the exhaust velocity to 50 - 100 km/sec. Such engines are called magnetoplasma rocket engines (MPRE).

It should be particularly noted that the potentialities of electric energy in jet engines were highly regarded, even before the dawn of USSR rocket engineering. For example, problems of this type were studied at the Leningrad /65 Gasdynamics Laboratory as long ago as 1929.

The possibility of obtaining a high exhaust velocity and the "economy" of an electrojet engine constitute extremely important advantages, but are not the only ones. The working fluid can be selected from a wide range of substances. As in the nuclear engine, a one-component, chemically inert nonexplosive working fluid can be used. It is also of importance that the operating conditions of an electrojet engine can be regulated by changing the electric feed parameters of the engine.

1. Types of Plasma Engines

Various schemes and projects of plasma engines* have frequently been dis-

* An electric system in which a working fluid is accelerated to produce (cont'd)

cussed in the USSR and foreign literature in recent years, and the test stand results of experimental models have been published. However, no systematization of plasma engines has been attempted. The classification of electrojet engines presented in Fig.1 is proposed as a first approximation. The classification

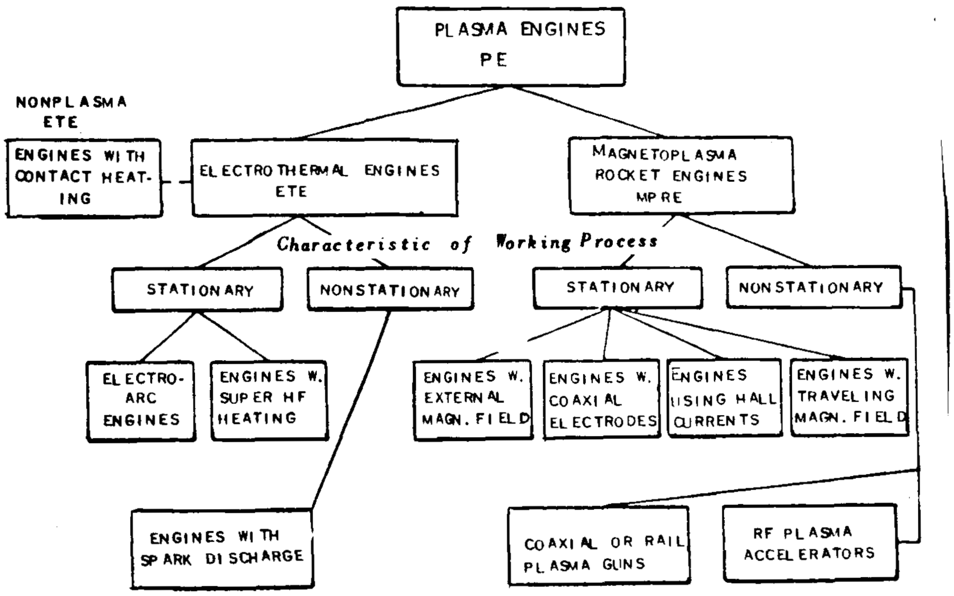


Fig.1 Classification of Plasma Engines

is based on an analysis of the operating principle of the prime mover, i.e., of the differences in the heating and accelerating systems for the working medium.

a) Electrothermal Engines

Such engines consist of a device for producing plasma and heating it to high temperatures, and a reaction nozzle of the type of a deLaval nozzle in which the working fluid is thermodynamically accelerated.

Electrothermal engines are sometimes identified with one particular member

---

* reactive thrust is termed a prime mover if considered apart from the energy source and energy conversion system. The system as a whole might be called an electrojet engine or an electrojet propulsive unit.

of this group, namely, the electric-arc engine. This is incorrect, since methods other than an arc discharge may also be successfully used to produce and heat the plasma: heating in a superhigh-frequency field, eddy-current heating, etc.

Electrothermal engines are important not only as an independent engine type but also as a component part of all types of magnetoplasma prime movers, used as a device to produce and pre-accelerate the plasma.

A schematic diagram of an electrothermal (electric arc) prime mover is given in Fig.2. The working fluid, in the form of a liquid or gas, is introduced into the arc-discharge chamber, from where it passes through the discharge zone, is ionized and heated to 5000 - 20,000°K. The resultant plasma, exhausted through a nozzle, then produces a reactive thrust.

The most important problem in designing an electric-arc engine is to produce electrodes that will resist excessive thermal stresses and erosion by the charged particles. To increase the electrode life, the trail of the arc dis- /66

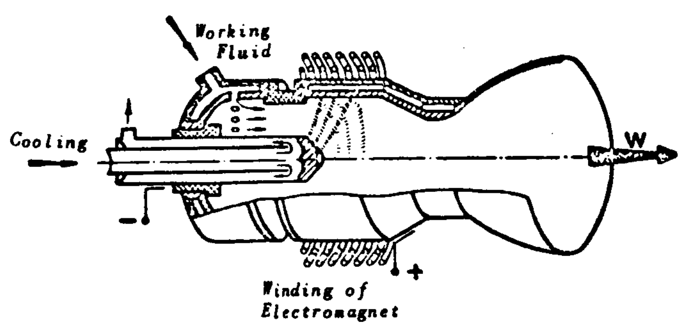


Fig.2 Schematic Diagram of Electrothermal Engine

charge can be made to move by a magnetic field, or its configuration can be varied, etc.

The electrodes can be given a higher resistance to the various stresses by cooling, which is done by forcing the working fluid through them. Special means for stabilization of the arc discharge are used to obtain the high temperatures.

Another important problem is the prevention of excessive heat losses from the working fluid and engine walls. The heat dissipation in the electrodes, insulators, and nozzle walls lowers the efficiency of the engine and shortens its useful life. Efficiencies up to 0.55 are obtained on the test stand, according to a report in No.19 of Missiles and Rockets (1964). Figure 3 shows the effect

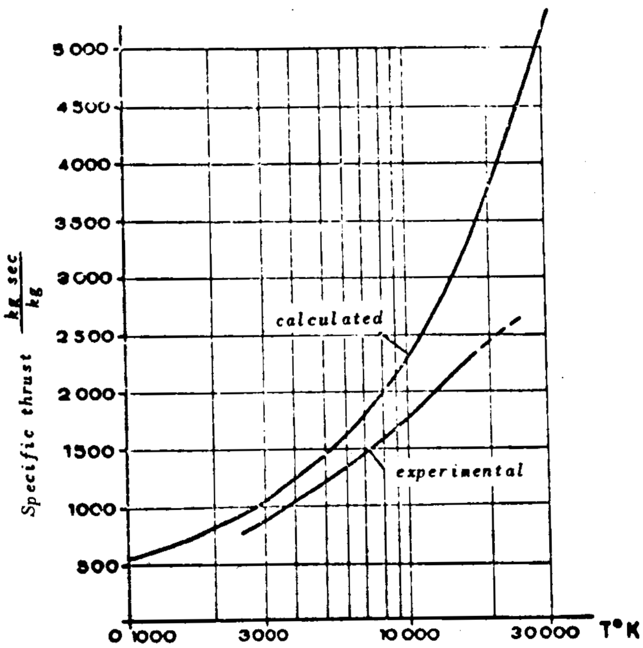


Fig.3 Specific Thrust of Electrothermal Engine vs. Temperature of Hydrogen ahead of Nozzle

of heat losses, by a comparison of the theoretical dependence of the specific thrust on the combustion-chamber temperature with an experimental curve.

b) Magnetoplasma Engines

To obtain an exhaust velocity of the order of 50,000 m/sec in an electrothermal engine, even when hydrogen is used as the working fluid, it would have to be heated to 100,000 - 150,000°K. This is impossible, even in a stationary process, owing to the immense heat dissipation from the engine walls.

Velocities of 50,000 - 100,000 m/sec are obtained only by accelerating the plasma through an electrothermal prime mover, constituting the source of the supersonic plasma jet in systems using various methods of acceleration in magnetic fields. Such engines are known as magnetoplasma engines. They are differentiated according to the method of plasma acceleration.

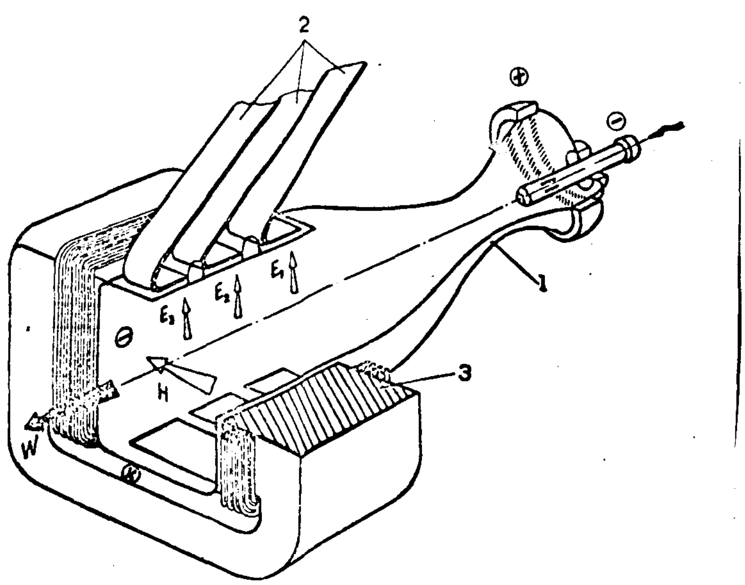


Fig.4 Plasma Accelerator with Crossed Magnetic and Electric Fields

A schematic diagram of a plasma accelerator, with crossed magnetic and electric fields is given in Fig.4.

From the nozzle of the electrothermal accelerator (1) the plasma enters the crossed-field accelerator. Electric current is fed to the electrodes by the bus bars (2).

The optimum voltage varies as the plasma advances through the accelerator.

It is, therefore, advantageous to divide the electrodes into several zones. The magnetic field may be uniform and can be produced by electromagnets (3) or by a permanent magnet. The use of cryogenic superconducting materials for the electromagnet windings gives good results in this and other layouts of magnetoplasma engines. The Lorentz force, produced by the interaction of the crossed electric and magnetic fields, is directed along the engine axis and accelerates the plasma.

The practical design of such an engine encounters new problems in addition to the others: reduction in the entering and leaving losses of the magnetic field; optimum distribution of the energy imparted to the plasma in the plasma generator and in the magnetic accelerator; determination of the optimum plasma temperature; etc.

If the temperature is not sufficiently high, the degree of ionization /67 of the working fluid will be low, and its reduced electric conductivity will make its efficient acceleration in the magnetic field impossible. However, raising the temperature of the fluid leads to a sharp increase in the heat dissipation.

A drawback of the crossed-field engine is the need for developed surfaces of the electrodes and magnetic conductors, which must also be cooled. This increases the hydraulic and thermal losses and limits the engine efficiency to 0.3 - 0.4.

Plasma engines with acceleration in their own magnetic field have a number of advantages. Among the continuous process accelerators, this type includes engines with coaxial electrodes and, in particular, one of the most promising types, namely, a unit with a front discharge (Fig.5).

In such a "front" engine, the current flows between the front electrodes and a "conductor"; plasma "bridges" are ejected and accelerated by their own magnetic field. The difficulty here is that the distribution of the large currents and the distribution of the velocity of the ejected plasma jets must be uniform both in magnitude and direction.

Periodic-action plasma accelerators include engines with a "traveling" magnetic field (Fig.6), "rail" accelerators (Fig.7), and other systems using time-variant magnetic fields and currents.

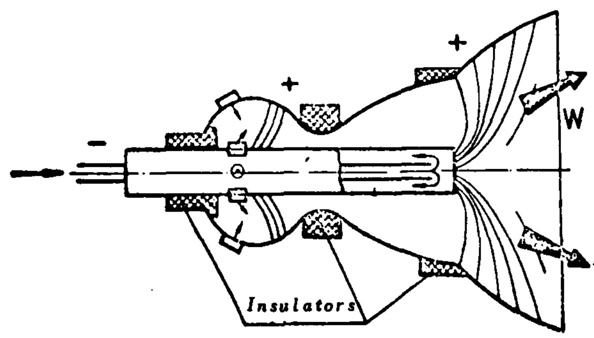


Fig.5 Schematic Diagram of Plasma Engine with Acceleration in its Own Magnetic Field (Coaxial Electrodes)

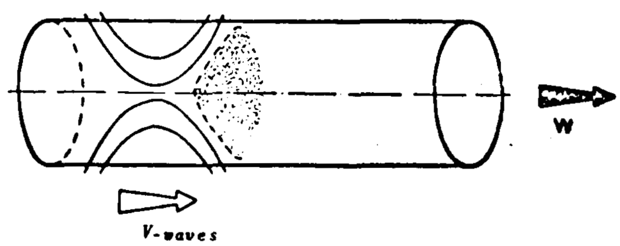
In magnetoplasma rocket engines with a traveling-wave magnetic field, the plasma is accelerated under the action of the pressure of the magnetic field. It plays the role of a piston expelling the plasma from the accelerator. A necessary condition in this case is a negligible penetration of the magnetic field into the portion of plasma being accelerated.

Engines with a traveling magnetic field occupy a position intermediate between stationary and nonstationary magnetoplasma rocket engines, since the process of efflux of the working fluid may be considered continuous, while the magnetic field is time-variant.

Coaxial and "rail" plasma guns use the same mechanism of plasma acceleration. High-tension current from a gang of capacitors flows through the electrodes and through the interconnecting plasma "bridges". A magnetic field, in which the plasma is accelerated, is induced around the electrodes.

This acceleration mechanism requires a gang of capacitors, whereas a TW accelerator does not. Further than that, the direct contact between plasma and electrodes is responsible for extensive erosion.

The action of a radio-frequency accelerator is similar to that of the last two types of engines. In this type, the role of the "piston" is played by strong periodic RF electromagnetic fields, from which the plasma is expelled and accelerated.



/68

Fig.6 Schematic Diagram of Accelerator with "Traveling" Magnetic Field

A magnetoplasma engine, using Hall currents (Fig.8), has a combined plasma-accelerating mechanism. In the strong radial magnetic field induced by several solenoids, and in contact with the central magnetic circuit, the Larmor radii, i.e., the radii of the circles around which the charged components of the plasma revolve in the magnetic field, differ greatly from each other. This generates a Hall current flowing about the axis of the engine. The current interacts with the radial magnetic field and produces the force that accelerates the plasma.

The mechanism of acceleration of the working fluid in such engines has not yet been adequately studied, but model tests have given encouraging results; in particular, an efficiency of about 50% and a specific thrust of the order of

$3000 \frac{kg \cdot sec}{kg}$ are obtainable. Engines of this type occupy a position intermediate between the plasma and ion engine.

2. Field of Application - Space

The thrust of plasma engines is still considerably less than their weight, not even speaking of the weight of the whole electrojet installation together with its power source.

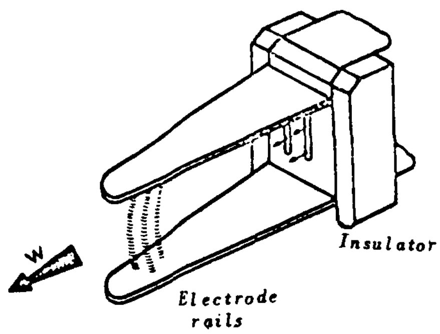


Fig.7 Schematic Diagram of Plasma Engine with "Rail" Accelerator

These weight characteristics are due to the complex and long conversion path from the power source (for instance, nuclear fuel) to the working fluid of the engine. However, in an atomic steam-turbine space device, the energy passes through the following stages: energy of fission - thermal energy in the fuel elements (FE) of the reactor - heating a heat transfer agent - generation of steam in the steam generator - production of mechanical energy in the turbine - production of electric energy in the electric generator - transfer of energy to the working fluid in the engine.

Simpler schemes have been developed in the meantime: The heat produced in the reactor is directly converted into electric energy, bypassing a turbine. These schemes include semiconductor, thermoemissive, and magnetodynamic electric generators. However, in such generators the path between energy production and acceleration of the working fluid is rather complex. It must also be borne in mind that losses are inevitable at each stage of energy conversion and that such losses are particularly great in the conversion of heat into electricity. The thermal energy of the losses must be dissipated into space by immense heat radiators.

Nevertheless, this complex process is the only way at present for overcoming the temperature barrier above which the strength of materials at the solid-state boundary cannot be increased further.

Owing to their small thrust, electrojet engines are unsuitable for flight in the atmosphere, for takeoff from the ground and for reaching the first cosmic velocity. Once in space however, i.e., along satellite orbits where the earth's gravitation is balanced by the centrifugal force, or in interplanetary space, such engines are highly useful. The reduction in working-fluid consumption by a factor of 20 - 50 permits a considerable increase in payload for long-range interplanetary flight systems. It is true that the low accelerations (10^{-3} to 10^{-4}) lengthen the travel time and require engines and power sources of great energy reserves, measured in thousands and tens of thousands of hours. However, in most cases, there is no other, more realistic, way. Today it is impossible to define which of the plasma engines is preferable. Many problems remain unsolved, and not all advantages of the various layouts have been fully studied.

Apparently, here again we have to do with a situation often met in technology, in which a full and unequivocal choice between two versions of a given technological solution of a problem is impossible. This was the case with Diesel and gasoline engines and will obviously be the same in considering the advantages of engines using chemical or nuclear fuel. For each technical solution there is an optimum field of application. The future of plasma engines of various types will be decided some day, and their application fields will be defined. Only long operating experience will determine their true merits. /69

The first experience with the use of plasma engines in the navigation system of a space vehicle, the Zond-2 space probe, showed them to be reliable and effective. The engines operated under various conditions, and were cut in repeatedly at a distance of about five million kilometers from the earth, where the pressure in the interplanetary medium is between 10^{-13} and 10^{-14} mm Hg.

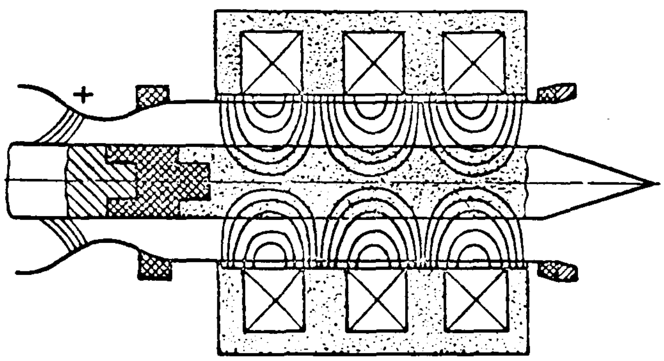


Fig.8 Hall-Current Magnetoplasma Engine

Next on the agenda is the extensive utilization of plasma engines in navigation systems and for stabilization of space vehicles, in orbit-correcting systems, and on manned spacecraft.

Today, when outer space is rapidly being conquered, it would be hard to overestimate the value of plasma engines; the future of space thrust systems belongs to this type of propulsive unit.

"The Soviet automated station Zond-2 has written yet another page in the chronicles of space achievements", stated Academician M.Millionshchikov. "The successful testing of plasma engines was for the first time performed on board a space vehicle... . Six such engines... maintained for a long time the required position of the probe relative to the sun. The usefulness of the plasma engine under space conditions has now been demonstrated in actual practice. Thus, plasma has been put to work in space for the first time anywhere in the world. This is a very significant event."

Electrojet engines of spacecraft will be powered by electric energy from atomic power plants. This will constitute a novel combination of a new type of engine with a new source of energy.

Soviet scientists and engineers were pioneers in the peaceful utilization of atomic energy, and today they have been the first to use plasma engines in space.

However, the road to these achievements was not an easy one. The cannons of World War II were still roaring, when Soviet scientists commenced their extensive penetration into science. Igor V.Kurchatov, the tireless organizer of important research projects, already at that time gave an affirmative answer to the question: "Atomic energy - to be or not to be". He was convinced that this constituted an extremely rich reserve for technology, and that its utilization for peaceful use would usher in a technical revolution.

In this research work, besides the technical problems, the war was a major obstacle. But finally the foe was vanquished. Still it took time, experimenting, and extensive searching by a large number of scientists, to overcome the scientific and technical difficulties. In 1954 the world's first atomic power station went into operation, and in 1964 the world's first reactor-converter "Romashka" was inaugurated.

"We have already taken the first steps toward the direct conversion of nuclear energy into electric energy...", writes Academician A.Aleksandrov. "The world's first reactor of this kind was built at the I.V.Kurchatov Institute of

Atomic Energy and has already operated over 3000 hours. Of course it is still in its infancy, but soon it will mature... .

"There can no longer be any doubt that the giant strength of atomic energy will change the whole face of our planet for the better, provided that all countries unite their efforts in the peaceful utilization of this strength."

The scientific search, started during World War II, is still continuing.